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The effects of multiyear and seasonal weather factors on incidence of Lyme disease and its vector in New York State

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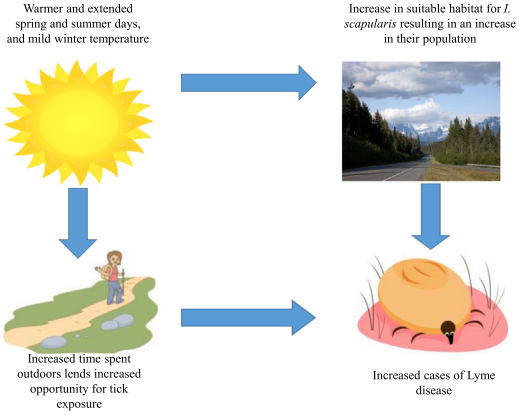
HIGHLIGHTS

- Lyme disease incidence has increased and has spread northward from coastal regions over time in New York State.
- The proportion of Lyme disease was higher among those aged 0–10 years and 40–50 years.
- Mild winter temperatures, extended spring, and warmer summer days appear to increase Lyme disease cases.
- Biologically relevant weather indicators in the index and previous year were used as unique tools in Lyme disease research.
- Males and residents living in Hudson Valley had higher proportions of Lyme disease.

GRAPHICAL ABSTRACT


Warmer and extended spring and summer days, and mild winter temperature
Increase in suitable habitat for I. scapularis resulting in an increase in their population
Increased time spent outdoors lends increased opportunity for tick exposure
Increased cases of Lyme disease

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ABSTRACT

Background: More frequent extreme weather and warmer weather due to climate change might change the spatiotemporal distributions of vector-borne diseases, including Lyme disease. However, limited studies have examined the associations of Lyme disease and its vectors with weather factors, especially multi-year and multi-weather factors related to vector life cycle.
Objectives: We investigated the associations between multi-year, unique weather indicators (relevant to tick and host activities) and Lyme disease incidence or documented *I. scapularis* encounters in New York State (NYS).
Methods: Using a generalized estimating equation model, we linked Lyme disease and tick (*I. scapularis*) data, obtained from the NYS Department of Health (NYSDOH) Communicable Disease Surveillance and Tick Identification Service, with weather data. We used a season-specific exposure index by considering days in different seasons with certain temperature and precipitation ranges, summer Palmer Hydrological Drought Index, and fitted linear regression models using generalized estimating equations.
Results: Lyme disease and *I. scapularis* encounters were modestly correlated (Spearman correlation = 0.60, *p*-value <0.001). The results indicate that summer Lyme disease cases and tick encounters may increase by 4–10%, per one day in spring with a minimum temperature range between 40 and 50 °F in the year of diagnosis and previous year. A day increase in summer with maximum temperature > 75 °F in the previous year was

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associated with 2% increase in summer disease counts. Mild winter days were associated with an increase in summer tick encounters.
Conclusions: Extended spring and summer days and mild winter temperatures appear to increase Lyme disease cases and tick exposure risk in NYS.

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1. Introduction

Lyme disease is endemic throughout New York State (NYS), and has become a major threat to public health. Lyme disease is the most common vector-borne disease in the United States (US), and is caused by a bacterial spirochete, *Borrelia burgdorferi* (Nelson et al., 2015). The primary vector for Lyme disease in the northeastern US is *Ixodes scapularis* (Say), commonly known as the blacklegged or deer tick. Ticks acquire spirochetes while feeding on the blood of an infected host, and later transmit the pathogen to small mammal reservoir hosts, or incidentally to humans, during subsequent blood meals (Schwartz, 2017).

A steady increase in Lyme disease cases has been observed in recent years in the US (Schwartz, 2017) and in other parts of the world (Mead, 2015). This increase has been attributed to improved disease surveillance, increased awareness, anthropogenic land use changes, and reporting errors (Schwartz, 2017), with climate change also identified as an important factor (Eisen et al., 2015). Changes in long-term climate patterns, particularly temperature and precipitation, may facilitate *I. scapularis* population growth due to an increase in suitable tick habitat and expansion in vector geographic range, as well as the acceleration and extension of the *I. scapularis* developmental cycle (Eisen et al., 2015; Ogden et al., 2014). As *I. scapularis* generally completes its life cycle in two years (Hayes et al., 2015; Lou and Wu, 2017), special weather conditions and composition during this long period likely impact its development and survival, and subsequently Lyme disease risk. Researchers have suggested that weather variations could also explain short-term fluctuations and seasonal patterns of Lyme disease and tick activity (Bacon et al., 2008; Moore et al., 2014). However, there is limited prior research that has examined the effects of weather factors on both Lyme disease and its vector. Among the available literature, inconsistent associations were found between temperature or precipitation and Lyme disease incidence (McCabe and Bunnell, 2004; Moore et al., 2014), or ticks (Hayes et al., 2015; Khatchikian et al., 2012; Schulze et al., 2009) due to use of different study design and weather indicators. Few studies used biologically relevant indicators by considering multi-year and multi-weather factors, which could better explain the influence of weather on Lyme disease incidence than a traditional single year or single weather variable.

Therefore, using biologically relevant weather indicators, we investigated the relationships between multiple weather indicators relevant to tick and host activities, and Lyme disease incidence and tick encounters in NYS during 1991–2006, and assessed if such associations were different by sociodemographic status. In addition, we described the temporal and spatial distributions of reported Lyme disease cases, and the temporal-spatial relationship between Lyme incidence and tick exposure.

2. Methods

2.1. Lyme disease and I. scapularis encounter data

Physicians in NYS are required by law to report Lyme disease cases to their local health department, while laboratory centers are required to report positive Lyme disease laboratory reports via an electronic surveillance system to the NYSDOH (Wharton et al., 1990). These electronic laboratory reports are sent to the local health department for public health investigation. The NYSDOH Communicable Disease Electronic Surveillance System contains information on date of birth, ZIP code-level address, sex, race/ethnicity, and occupation for each reportable Lyme disease case. We used the 1991–2006 data rather than more recent data because Lyme case data from a random sample rather than from all cases were collected after 2006 in result of a workforce shortage in NYS. As a majority of Lyme cases occur in summer, the seasonal weather effect on summer cases is one of this study's main focus. Data on tick encounters was obtained from the NYSDOH Tick Identification Service, a passive tick statewide surveillance program operational from 1989 to 2011. For the analyses conducted in this study, we included only confirmed Lyme disease cases and records of locally-acquired *I. scapularis* obtained from hosts reporting no history of travel prior to finding and removing a tick, from 1991 to 2006.

The ZIP code-level address of each reported Lyme disease case was geocoded using MapMarker Plus. The map of geocoded patient addresses was overlaid onto weather division maps using MapInfo 8.5®; disease counts were aggregated by weather division for analysis, and census data from 1990 and 2000 was used to estimate population. Tick encounter reports were geocoded by the host/patient address.

2.2. Weather data

Temperature, snow, and precipitation data were obtained from the US Historical Climate Network (monthly data), and drought data was obtained from the National Climatic Data Center (NCDC, 2013a). The data was compiled to create 10 weather divisions: Western Plateau, Eastern Plateau, Northern Plateau, Coastal Area, Hudson Valley, Mohawk Valley, Champlain Valley, St. Lawrence Valley, Great Lakes, and Central Lakes. The individual weather station data were downloaded and averaged within each climate division.

As season-specific temperature and precipitation ranges were found essential for tick survival and fecundity, those special weather indicators related to human and host activities were identified from previous literature (Lindgren and Gustafson, 2001; Lindgren et al., 2006) as described in Table 1. These indicators were then linked with summer Lyme disease incidence and tick encounters in this study. We considered the period from December through February as winter, March through May as spring, June through August as summer, and September through November as fall. Since extreme winter temperatures and snow depth may impact tick survival and development, we derived winter indices using both temperature and snow cover data (Lindgren and Gustafson, 2001; Lindgren et al., 2006). We considered the number of mild winter days (defined as days with temperature > 32 °F and snow depth < 12 in.), number of severe winter days (defined as days with temperature < 15 °F and snow depth ≥ 12 in.), and number of moderate winter days (defined as days with temperature < 15 °F and snow depth < 12 in.) as potentially important predictors (Lindgren et al., 2006). We also used combinations of snow cover and temperature in an attempt to capture the effect of both temperature and snow cover on *I. scapularis* survival. Optimal spring temperature ranges for tick questing and for molting of larvae to nymphs have been suggested to be 5–8 °C (41–46.4 °F) and 8–11 °C (46.4–51.8 °F), respectively (Lindgren and Gustafson, 2001; Lindgren et al., 2006). Therefore, we considered number of spring days with minimum temperature ≥ 40 °F in the same year (t) and previous year (t-1) in the analysis. Summer season predictors of

Table 1
Bivariate models for predictors of Lyme disease counts[a] and *I. scapularis* encounters[a] during summer in New York State, 1991–2006.

Weather indicator	Lyme disease	*I. scapularis*
	β[b] (95% CI)	β[c] (95% CI)
Winter		
Mild Winter Days (t)	0.04 (0.00, 0.08)*	0.05 (0.00, 0.09)**
Mild Winter Days (t-1)	0.04 (0.00, 0.08)*	0.08 (0.03, 0.12)**
Severe Winter Days (t)	−0.01 (−0.02, 0.01)	0.00 (−0.02, 0.02)
Severe Winter Days (t-1)	−0.01 (−0.03, 0.00)*	−0.02 (−0.03, 0.00)*
Moderate Winter Days (t)	−0.01 (−0.03, 0.00)*	−0.02 (−0.04, 0.00)**
Moderate Winter Days (t-1)	−0.01 (−0.03, 0.00)*	−0.03 (−0.04, −0.01)**
Spring		
Tmin 40–45 °F (4.44–7.22 °C) (t)	0.10 (0.05, 0.15)**	0.12 (0.08, 0.17)**
Tmin 40–45 °F (4.44–7.22 °C) (t-1)	0.09 (0.04, 0.14)**	0.08 (0.03, 0.13)**
Tmin 45–50 °F (7.22–10 °C) (t)	0.08 (0.03, 0.14)**	0.07 (0.01, 0.13)**
Tmin 45–50 °F (7.22–10 °C) (t-1)	0.09 (0.03, 0.14)**	0.07 (0.01, 0.13)**
Tmin >50 °F (>10 °C) (t)	0.02 (−0.01, 0.05)	−0.01 (−0.05, 0.02)
Tmin >50 °F (>10 °C) (t-1)	0.02 (−0.01, 0.06)	0.02 (−0.01, 0.06)
Summer		
Tmax >75 °F (>23.89 °C) (t)	0.04 (0.02, 0.06)**	0.02 (0.00, 0.04)*
Tmax >75 °F (>23.89 °C) (t-1)	0.04 (0.02, 0.06)**	0.02 (0.00, 0.04)**
PHDI (t)	−0.01 (−0.11, 0.08)	0.03 (−0.07, 0.13)
PHDI (t-1)	−0.05 (−0.14, 0.05)	−0.05 (−0.15, 0.06)
Wet Days (t)	0.00 (−0.02, 0.03)	0.02 (−0.01, 0.05)*
Wet Days (t-1)	−0.01 (−0.03, 0.02)	0.00 (−0.03, 0.03)
Fall		
Tmax >75 °F (>23.89 °C) (t-1)	0.09 (0.05, 0.12)**	0.05 (0.01, 0.09)**
Wet Days (t-1)	−0.02 (−0.05, 0.01)*	−0.01 (−0.04, 0.02)

Abbreviations: CI, Confidence Intervals; PHDI, Palmer Hydrological Drought Index.
(t) indicates predictor variable in the same year of Lyme disease report/*I. scapularis* encounter and (t-1) indicates predictor variable in the previous year. Mild winter days indicate number of days with temperature > 32 °F (0 °C) and snow depth < 12 in. Severe winter days indicate number of days with temperature < 15 °F (−9.44 °C) and snow depth ≥ 12 in. Moderate winter days indicate number of days with temperature 15 °F (−9.44 °C) and snow depth < 12 in. Tmin 40–45 indicates number of days with minimum temperature between 40 and 45° F. Tmin 45–50 indicates number of days with minimum temperature between 45 and 50° F. Tmin >50 indicates number of days with minimum temperature > 50° F. Tmax >75 indicates number of days with maximum temperature > 75° F. Wet days indicates number of days with precipitation >0.05 in. but <1 in.
[a] Log transformed.
[b] Adjusted for region specific-log total population and year, and retained weather indicators in the model.
[c] Adjusted for region specific-log area and year, and retained weather indicators in the model.
* 0.05 < p-value <0.20.
** p-value <0.05.

Lyme disease and tick exposures included number of days with maximum temperature > 75 °F (T_{max} > 75 °F) (a favorable temperature for human activity), and number of wet days (defined as days with precipitation between 0.05 and 1 in.). The effect of drought and wet conditions on Lyme disease and tick encounters in the summer were assessed by the mean summer Palmer Hydrological Drought Index (PHDI) (Schauber et al., 2005; Subak, 2003), where higher PHDI values imply more moisture. The index is based on factors such as precipitation totals, temperature, evapotranspiration, soil run-off, and soil recharge (NCDC, 2013b). A constant was added to raw PHDI scores to transform them into a positive scale. The number of days in the fall with maximum temperature > 75 °F and number of wet days (precipitation between 0.05 and 1 in.) were also selected as variables. Since the life-cycle of the tick is two years, we included weather indices in two years prior to Lyme disease incidence in the analysis, i.e., various weather indicators in the same year when Lyme disease was identified (t), and those in the preceding year (t-1) by season.

2.3. Statistical analysis

Descriptive statistics were produced using univariate and bivariate analyses. The chi-square test was used to compare distributions of categorical variables. We fitted linear regression models using generalized estimating equations to examine the associations between weather variables and summer Lyme disease incidence and *I. scapularis* encounters; a generalized estimating equation provided population-average estimates accounting for correlation between observations within a cluster. We specified climatic divisions as clusters to account for within-division correlations. The unit of analysis was climatic division-year, calculated as the number of the divisions multiplied by the number of years in the study. For Lyme disease analyses, the response variable was the natural logarithm (ln) of the number of Lyme disease cases in the division for a given year. If there were zero case counts in any climatic division-year, we added a constant (0.001) to the zero count before log-transforming, as the prior literature did. Division-specific population and year were also entered as covariates to adjust for population and temporal autocorrelation. For tick analyses, the response variable was the natural log of locally acquired *I. scapularis* submitted from each division for a given year. The model was also adjusted for area of the weather division and year. All weather indices that were significant in bivariate analysis at p-value <0.20 were included in the initial model, and a backward elimination procedure was employed for model building. We specified an independent correlation matrix and quasi-likelihood information criteria was also considered for the selection of variables and working correlation matrix (Pan, 2004). Model-based variance estimates were used instead of empirical variance estimates, due to the small number of clusters (Horton and Lipsitz, 1999; Fitzmaurice et al., 2011). Regressions were performed with SAS 9.2 (SAS Institute Inc., 2004). All the statistical tests were two-tailed and are considered statistically significant at p-value <0.05.

3. Results

3.1. Univariate and bivariate results

A total of 67,119 Lyme disease cases and 18,787 locally acquired *I. scapularis* were reported during 1991–2006, of which 64,871 disease cases and 18,553 tick reports were able to be geocoded. The proportion of reported cases was highest in summer (65.4%, n = 42,398), followed by fall (16.7%, n = 10,830). *I. scapularis* encounters were highest in fall (42.6%, n = 7899), followed by spring (35.7%, n = 6624) and summer (17.6%, n = 3273), with nymph encounters highest in summer and adult tick encounters highest during spring and fall (data not shown). Overall, the proportion of reported Lyme disease cases was highest in the Hudson Valley (76%, n = 49,099) and Coastal Area (20%, n = 12,764). Of the total *I. scapularis* encounters documented, approximately 64% were submitted from the Hudson Valley (data not shown).

Fig. 1 shows the temporal and spatial distribution of Lyme disease cases in NYS. In 1991, the disease was concentrated in the Coastal Area and mid to southern Hudson Valley, and has since spread steadily northward, resulting in an established presence in the northern Hudson Valley by 2006. Supplemental Material, Fig. S1 shows the temporal distribution of Lyme disease and vector tick encounters in the Hudson Valley and Eastern Plateau, the two weather divisions with the highest number of *I. scapularis* encounters, as well as the state-wide temporal trends. Steady increases in Lyme disease cases and vector tick encounters were observed in both divisions as well as statewide.

In bivariate analysis (Table 1), Spring days (T_{min} 40–45 °F), Spring days (T_{min} 45–50 °F), and summer days (T_{max} > 75 °F) in the year of diagnosis and previous year, and fall days (T_{max} > 75 °F) in the previous year were positively associated with Lyme disease incidence in the summer. Similarly, mild winter days, Spring days (T_{min} 40–45 °F), Spring days (T_{min} 45–50 °F), and summer days (T_{max} > 75 °F) in the year of diagnosis and previous year, and fall days (T_{max} > 75 °F) in the previous

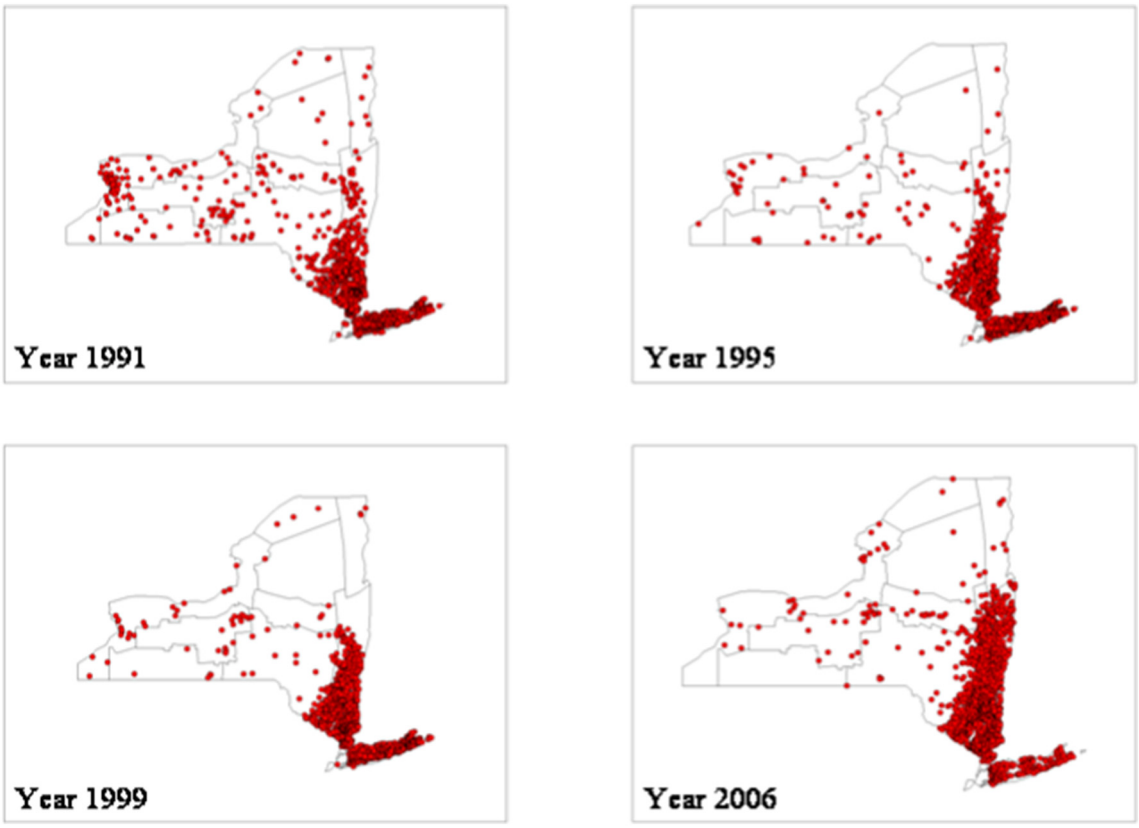

Fig. 1. Spatiotemporal Distribution of Lyme disease in New York State.

year were associated with an increase in *I. scapularis* encounters in the summer. Moderate winter days in the previous year were associated with a decrease in *I. scapularis* encounters.

Table 2 presents the demographic and geographic distribution of reported Lyme disease cases and *I. scapularis* encounters in NYS during summer. Fifty two percent of the disease cases were male. The age distribution of the infected individuals was bimodal, with greater incidence of the disease among those aged 0–10 years and 40–50 years (data not shown). Of the total reported *I. scapularis* encounters (n = 3252), 66.5% were nymphs and 29.4% were adults. Approximately 74% of submitted ticks and 78% of reported cases were from the Hudson Valley. Although the Coastal Area had the second greatest number of reported cases in NYS (18.1%), *I. scapularis* encounters were relatively low for that division (2.2%). The number of locally acquired *I. scapularis* submitted were low in relation to the higher number of Lyme disease cases in general. As described in Fig. 2, Lyme disease cases and *I. scapularis* encounters were modestly correlated (Spearman Correlation: 0.60, $p < 0.001$).

3.2. Multivariable results

In the multivariable model (Table 3), spring days (T_{min} 40–45 °F) in the year of diagnosis and previous year were associated with increased summer Lyme disease risk ($\beta = 0.08$, 95% confidence interval (CI) = 0.03, 0.12, and $\beta = 0.06$, 95% CI = 0.01, 0.11, respectively), as were spring days (Tmin 45–50 °F) in the year of diagnosis and previous year ($\beta = 0.06$, 95% CI = 0.01, 0.11, and $\beta = 0.07$, 95% CI = 0.02, 0.13, respectively). In other words, a day increase in spring days with minimum temperature between 40 °F–50 °F corresponded to a 6–8% increase in summer Lyme disease cases. Spring days ($T_{min} > 50$ °F) in the previous year was also associated with increased Lyme disease risk ($\beta = 0.04$, 95% CI = 0.01, 0.06), which corresponded to a 4% increase in disease risk. Summer days ($T_{max} > 75$ °F) in the year of diagnosis as well as in the previous year was associated with increased disease risk (2%)).

Reported *I. scapularis* encounters in summer were positively associated with mild winter days in the previous year ($\beta = 0.07$, 95% CI = 0.03, 0.11), spring days (T_{min} 40–45 °F) in the year of diagnosis and previous year ($\beta = 0.10$, 95% CI = 0.05, 0.15, and $\beta = 0.04$, 95% CI = 0.00, 0.09, respectively), and spring days (T_{min} 45–50 °F) in the previous year ($\beta = 0.06$, 95% CI = 0.00, 0.12).

Age- and sex-stratified regression analysis to investigate the association between Lyme disease and weather variables did not demonstrate any effect modification by these demographics (data not shown).

4. Discussion

We observed both spatial and temporal variations in Lyme disease cases and tick encounter reports in NYS. The greatest number of Lyme disease cases was seen in the Hudson Valley and Coastal Area throughout the study period. The disease has increased and spread steadily towards latitudes that are more northern over time. The northward expansion of Lyme disease over time was also reported by prior studies and may potentially be attributed to the expansion of suitable tick habitat or weather/other conditions enabling tick colonization and establishment (Mills et al., 2010; Ogden et al., 2014). We also found that reported Lyme disease was higher among those aged 0–10 years and 40–50 years and higher among males than females, which were consistent with previous literature (Nelson et al., 2015; Schwartz, 2017). Longer duration of time spent outdoors among these age groups and males may partially explain the higher disease proportions among these groups.

While previous studies have reported strong correlation between ticks collected from active sampling and Lyme disease incidence (Falco et al., 1999; Hayes et al., 2015; Stafford et al., 1998), we detected only a modest correlation between reported tick encounters (obtained

Table 2
Demographic and geographic distribution of Lyme disease cases and *I. scapularis* encounters during summer in New York State, 1991–2006.

Characteristics	Lyme disease (n = 42,398)	*I. scapularis* (n = 3273)
	n (%)	n (%)
Age of patients (years)*,a		
0 to <10	6530 (15.51)	–
10 to <20	5157 (12.25)	–
20 to <30	3178 (7.55)	–
30 to <40	5340 (12.68)	–
40 to <50	7137 (16.95)	–
50 to <60	6263 (14.87)	–
60 to <70	4614 (10.96)	–
70 to <80	2892 (6.87)	–
80 to <90	900 (2.14)	–
>90	99 (0.24)	–
Sex of patients*,b		
Male	22,120 (52.19)	–
Female	20,261 (47.81)	–
Tick stage*,c		
Adult	–	956 (29.4)
Larva	–	135 (4.15)
Nymph	–	2161 (66.45)
Weather division*		
Western Plateau	54 (0.13)	21 (0.64)
Eastern Plateau	1054 (2.49)	311 (9.5)
Northern Plateau	59 (0.14)	22 (0.67)
Coastal Area	7690 (18.14)	72 (2.2)
Hudson Valley	33,025 (77.89)	2416 (73.82)
Mohawk Valley	73 (0.17)	147 (4.49)
Champlain Valley	38 (0.09)	74 (2.26)
St. Lawrence Valley	17 (0.04)	9 (0.27)
Great Lakes	243 (0.57)	72 (2.2)
Central Lakes	145 (0.34)	129 (3.94)

* P-values from Chi-square tests <0.0001.
[a] Missing n = 288
[b] Missing n = 19.
[c] Missing n = 21.

Table 3
Multivariable models[a] for predictors of Lyme disease counts[a] and *I. scapularis* encounters[a] during summer in New York State, 1991–2006.

Weather indicator	Lyme disease	*I. scapularis*
	β[b] (95% CI)	β[c] (95% CI)
Winter		
Mild Winter Days (t-1)	-[d]	0.07 (0.03, 0.11)
Spring-[d]		
Tmin 40–45 °F (4.44–7.22 °C) (t)	0.08 (0.03, 0.12)	0.10 (0.05, 0.15)
Tmin 40–45 °F (4.44–7.22 °C) (t-1)	0.06 (0.01, 0.11)	0.04 (0.00, 0.09)
Tmin 45–50 °F (7.22–10 °C) (t)	0.06 (0.01, 0.11)	-[d]
Tmin 45–50 °F (7.22–10 °C) (t-1)	0.07 (0.02, 0.13)	0.06 (0.00, 0.12)
Tmin >50 °F (>10 °C) (t-1)	0.04 (0.01, 0.06)	-[d]
Summer		
Tmax >75 °F (>23.89 °C) (t)	0.02 (0.01, 0.04)	-[d]
Tmax >75 °F (>23.89 °C) (t-1)	0.02 (0.01, 0.04)	-[d]

Abbreviations: CI, Confidence Intervals.
All the variables indicator in the model are statistically significant (p-value <0.05). (t) indicates predictor variable in the same year of Lyme disease report/*I. scapularis* encounter and (t-1) indicates predictor variable in the previous year. Mild winter days indicate number of days with temperature >32° F (0 °C) and snow depth <12 in.
[a] Log transformed.
[b] Adjusted for region specific-log total population and year, and retained weather indicators in the model.
[c] Adjusted for region specific-log area and year, and retained weather indicators in the model.
[d] Indicates that the variables were either dropped out from the models or were not included in the initial model.

from our passive sampling) and Lyme disease incidence. The number of locally acquired, *I. scapularis* nymphs submitted was low in relation to the high number of Lyme disease cases; this could be due to people not recognizing and removing tiny *I. scapularis* nymphs, or reporting fatigue as people stop submitting ticks from regions because they know what they look like and do not need a formal identification. It may also reflect the limitation of a passive sampling of tick encounters compared to an active registry.

We found that mild winter days in the previous year were positively associated with summer *I. scapularis* encounters. Previous studies have also shown that mild winters are generally favorable for both tick abundance and Lyme disease (Daniel et al., 2008; Schauber et al., 2005; Subak, 2003). It is likely that mild winter facilitates the overall survival of early developmental stages of Ixodid ticks including eggs and larva consequently leading to increased tick population.

In our study, an increase in the number of spring days in the same year with minimum temperature range between 40 and 50 °F in general

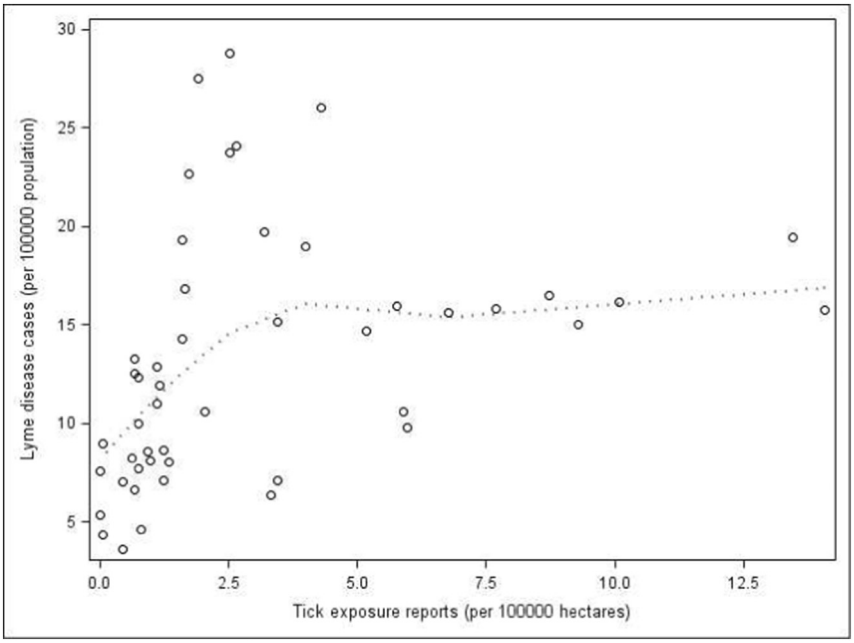

Fig. 2. Relationship between Lyme disease incidence and *I. scapularis* encounters in Hudson Valley in June, July, and August 1991–2006.

was associated with both increased summer Lyme disease incidence and summer tick encounters. Similar associations were detected for tick borne encephalitis in Sweden (Lindgren and Gustafson, 2001; Lindgren et al., 2006). Spring temperatures ranging from 45 to 50 °F favor the larvae-to-nymph transformation, and spring temperatures of 40–45 °F foster early activity of ticks. Therefore, an extended number of spring days may increase *I. scapularis* abundance and activity at a time when people are likely to be working and recreating outdoors, consequently increasing Lyme disease incidence. We observed that increase in summer days with maximum temperature > 75 °F were significant predictors of summer Lyme disease risk, which reflects increased human activity.

We did not observe any association between summer Lyme disease or tick encounters and PHDI or precipitation indicators in the multivariable models. Positive associations between Lyme disease and humidity indicators have been reported in previous studies (Bennet et al., 2006; Schauber et al., 2005; Subak, 2003), whereas findings regarding Lyme disease or tick indicators and precipitation indicators are not consistent (Khatchikian et al., 2012; Ostfeld et al., 2006; Schauber et al., 2005; Schulze et al., 2009). It is likely that weather indicators such as PHDI and precipitation may not capture the complex relationships between microclimatic environmental factors and the behavior and activity of *I. scapularis*. Instead, indicators such as cumulative hours below suboptimal humidity (i.e., < 82%) may be more relevant (Berger et al., 2014).

Our study has several strengths. We used region-specific climatic data for exposure assignment to minimize misclassification of exposure, unlike other US studies (Schauber et al., 2005; Subak, 2003), in which weather data from the region with the highest number of Lyme disease reports was assigned to cases from all regions. In addition, we were also able to incorporate snow cover data to quantify winter severity, use multi-year and seasonal-specific meteorological factors, and utilize biologically relevant weather factors to link with the health outcomes. This is also one of the few studies investigating the effects of multi-weather factors on both Lyme disease and tick encounter by using statewide registry data to confirm the biological plausibility of our results.

There are several limitations of this study. Although biologically relevant weather factors were considered, some potential confounders, such as data on abundance of hosts, habitat structure, and human activity pattern may be important predictors for *I. scapularis* establishment, infected host prevalence, and subsequent disease contraction by humans (Ostfeld et al., 2006; Prusinski et al., 2006). Our statistical model adjusted for area of the weather division and year, which addressed the concern of temporal/spatial difference. Another limitation is that we did not know the infection status of the ticks submitted for identification, as prior research reported that prevalence of infected ticks, rather than overall prevalence, may determine Lyme disease incidence (Ashley and Meentemeyer, 2004; Schauber et al., 2005). Our coauthors from the NYSDOH are working on another project to examine the infected status and pathogen DNA following this study. Additionally, an undetermined level of misdiagnosis and/or under-reporting of Lyme disease cases may have affected the results, which has been a common limitation for all studies in Lyme disease (Stricker and Johnson, 2014); however, we expect the disease misclassification or under-reporting to be non-differential among the climate zones, and therefore towards the null.

Also, unlike active sampling of host-seeking ticks, passive surveillance may not capture true tick density. For instance, reported nymph and larva counts during winter were very low which reflects reporting bias due to reduced outdoor activity and low seasonal tick prevalence. However, our *I. scapularis* encounter data inherently take human activity and behavior into account, both of which contribute to risk of acquiring a tick-borne disease. Future analysis, including host-seeking tick population data, recently collected by the NYSDOH from across NYS is warranted to address some of these limitations.

Lyme disease represents a significant public health burden and is associated with considerable healthcare costs; the total nationwide healthcare cost for Lyme disease in 2002 was estimated to be around $203 million in the US (Zhang et al., 2006). Proliferation and habitat expansion of *I. scapularis* in the future is likely, given the current and projected trends in temperature increase (Insaf et al., 2013). This study's findings would help public health agencies and policy makers understand the unique associations between multiple weather exposures and both tick and Lyme disease risk, and the resulting vulnerability to high-risk populations, as well as develop public awareness education programs for tick-borne diseases. Our study also demonstrates the use of biologically relevant weather indicators as unique tools in this research area.

5. Conclusions

Lyme disease incidence has increased and spread steadily towards northern latitudes over time in NYS. The proportions of Lyme disease were higher among those aged 0–10 years and 40–50 years, males and the residents living in Hudson Valley. Summer Lyme disease incidence and *I. scapularis* encounters are positively associated with warm winter temperature and extended spring days in NYS. The effects of precipitation and relative humidity seem more complex, and therefore, further research with similar hypothesis is needed to confirm our findings.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.02.123.

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Conflict of interest

The authors declare that they have no actual or potential competing financial interests.

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